REPORT No. 35

THE STRENGTH OF ONE-PIECE SOLID, BUILT-UP, AND LAMINATED WOOD AIRPLANE WING BEAMS

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BY

JOHN H. NELSON

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THE STRENGTH OF ONE-PIECE SOLID, BUILT-UP AND LAMINATED WOOD AIRPLANE WING BEAMS.

By John H. Nelson.

The present war has caused an unprecedented demand for selected spruce for airplane construction. The increased demand has necessarily caused a greatly increased output. However, the magnitude of the requirements and methods of construction, whereby a large part of the selected stock is wasted in the construction of the one-piece beams, makes the problem of furnishing sufficient selected stock a very serious one, even with the enlarged output.

The remedy for this condition lies either in the discovery of a perfectly satisfactory substitute for the spruce now used, or in the development of some method of construction which will conserve the present supply by utilizing more of the selected material.

In an attempt to find a solution of the above problem, certain experiments were conducted during the past year at the Bureau of Standards. Tests were made on several of the more common woods to determine their suitability as substitutes for spruce. Further, beams built up of three pieces or of laminated construction have been tested to determine their strength in comparison with the one-piece construction.

The built-up and laminated constructions eliminate the waste involved in the process of cutting an **I** section from solid timber. In such construction it is also possible to use wood in short lengths, and though the cost of manufacturing built-up beams is somewhat greater than that of producing the solid beams, the cost of the raw material utilized is much less than the cost of the carefully selected timbers used for solid beams.

The purpose of this report is to summarize the results of all wood airplane wing beams tested to date in the Bureau of Standards laboratory in order that the various kinds of wood and methods of construction may be compared.

All beams tested were of an **I** section and the majority were somewhat similar in size and cross section to the front wing beam of the Curtiss JN–4 machine.

As to methods of construction, the beams may be classed as (1) solid beams cut from solid stock; (2) three-piece beams, built up of three pieces, web and flanges glued together by a tongue-and-groove joint; and (3) laminated beams built up of thin laminations of wood glued together.

This report includes three sets of test data:

(*a*) Fourteen solid beams, designated by English numerals in this report, were made in the Bureau of Standards shop. The purpose of these tests was (1) to determine the suitability of fir and cypress woods for airplane use, compared with Sitka spruce, and (2) to determine whether a plain rectangular **I**-section beam possessed any advantage over the oblique **I**-section beam, which is used at present, other than the advantage of simplicity in shop practice.

(*b*) Fifteen beams were submitted for test by the Naval Aircraft Factory, Philadelphia. These beams were designated by the Roman No. I, to identify the series, followed by subnumbers 5 to 19, to indicate the beams of the series. These beams were all built of spruce; seven were solid beams and eight were three-piece beams. These tests were made (1) to determine the advantage of the rectangular **I**-section over the oblique **I**-section, if any; (2) to compare three-piece beams with solid beams; and (3) to determine the effect of splicing three-piece beams.

(*c*) Twenty-three laminated beams were submitted for test, 14 by the West Woodworking Co. of Chicago, and 9 by Aeronautical Equipment (Inc.), of New York City. These beams are designated by Roman numerals throughout this report. Four of these beams were built of cypress wood and the remainder of spruce; a number of the spruce beams had additional laminations of hardwood placed advantageously in the beam section. These beams were tested to determine the merits of laminated beam construction, with the view of using it as a substitute for solid beams.

All beams were 90 inches long. A sketch of each beam section, giving its dimensions and properties, is shown on the following pages. Photographs are also shown of sections cut from laminated beams I to XX.

METHODS OF TEST.

All beams were tested for transverse strength by two-point loading. Load was applied at points 24 inches from supports in an 84-inch span.

A vibratory or repeated stress test was made on beam No. X to note the effect of vibrations upon a laminated beam. The beam was loaded repeatedly to a stress of about two-thirds the elastic limit. Applications of stress occurred at the rate of 74 per minute for 14½ hours. It was then loaded to rupture and the results noted.

Shear tests of glued joints were made on sections cut from a number of the first laminated beams, to determined the ability of the glue joints, between the web and flanges, to withstand shear stresses. To avoid unnecessary columns of figures, the glue shear test data will be omitted from this report. The results showed the glue joint to be stronger in shear than the wood web section in the case of relatively dry test specimens, and also in the case of moist specimens exposed for four and one-half days in a humidity chamber (relative humidity 65 per cent aturation, at 65° F) before being tested.

GENERAL CONCLUSIONS.

While this report does not contain data from an exhaustive series of tests on built-up beam constructions, it is apparent that the results obtained are conclusive enough to warrant the acceptance of certain definite conclusions. This is true notwithstanding the fact that the work was carried out under conditions which precluded certain desirable scientific requirements such as identical material for all beams.

1. It is apparent that beams of fir can be produced which, weight for weight, will prove as strong as those made of spruce, but will not, however, show quite the same stiffness; further, that cypress can not be considered as a satisfactory substitute for spruce. (Cf. data on beams 1 to 15 solid beams; beams VII and VIII of laminated construction.)

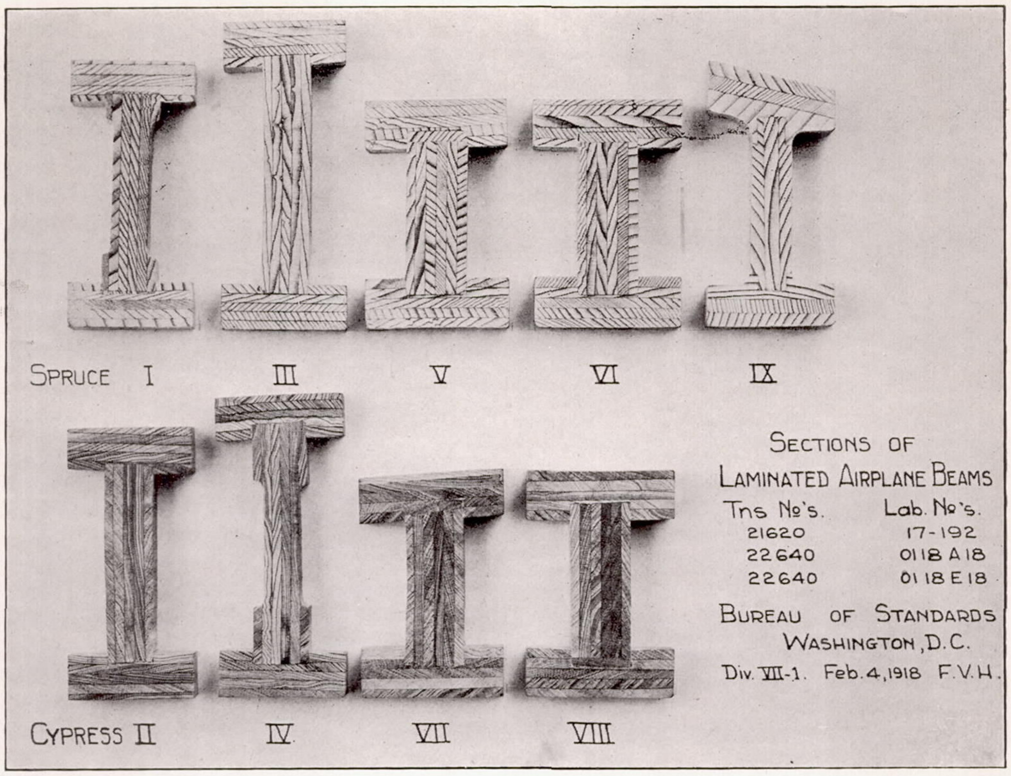
2. On the basis of equal section moduli the rectangular sections are stronger than the oblique sections. (Cf. data on beams 1 to 15 solid.)

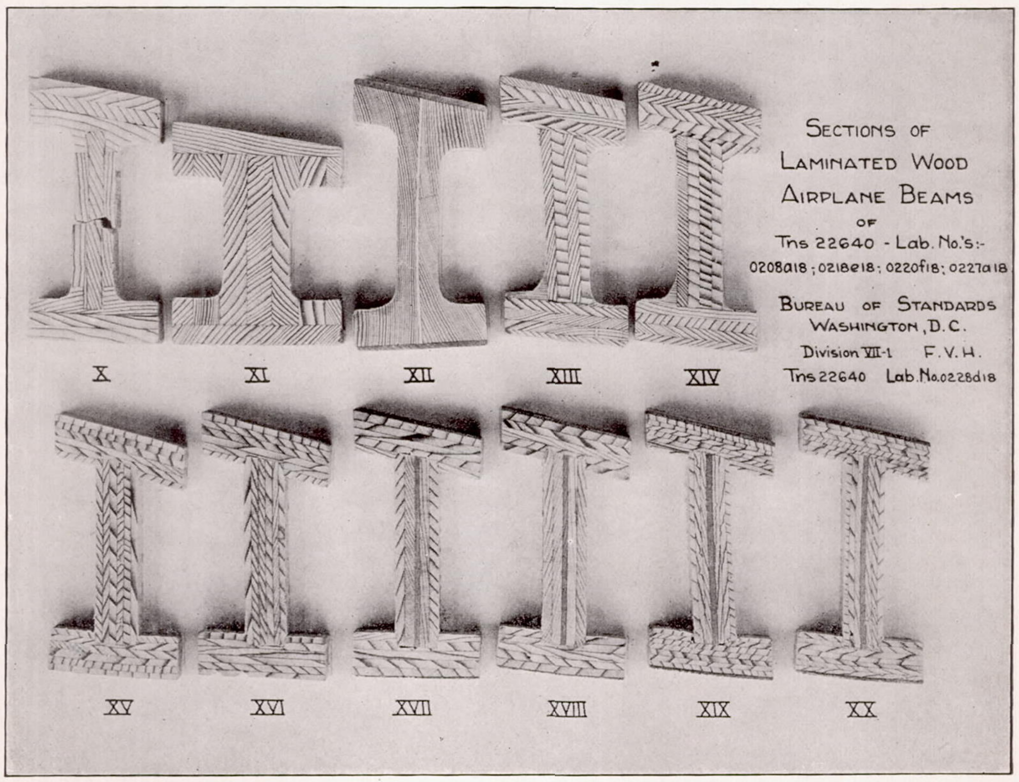
3. Beams made up of three pieces can be produced which will be as strong as the solid beam construction. While these tests indicate that a larger variation in strength may be expected with the three-piece beams, such variation is apparently not more than that which is ordinarily expected with wood construction. The solid beams with which the three-piece beams were compared gave remarkably consistent strengths for wood construction.

4. Beams of the laminated construction can be built which will be as strong as the one-piece, (solid) construction.

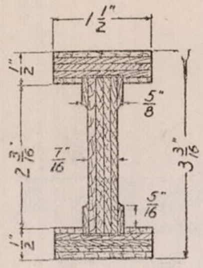
5. The details of construction employed in three-piece and laminated constructions have a large influence on the strength of the finished beam:

(*a*) Three-piece and laminated beams are not weakened when properly spliced. Scarf joints only are permissible for splices. Butt joints are unsatisfactory. A suitable scarf joint is made by cutting the ends to be spliced with a slope of three-fourths in 10; these ends are then overlapped and glued. (Cf. beams I–5 to I–19 and remarks on beams I to IV, XVI to XVIII, and XXIII.)



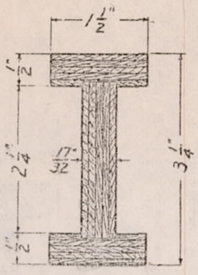


146743—19. (To face page 6.)



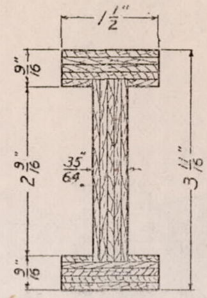
I = 3.222

Section of Beam-I



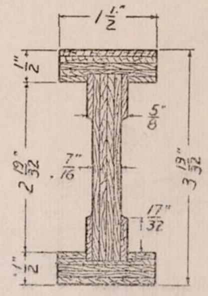
I = 3.37

Section of Beam-II



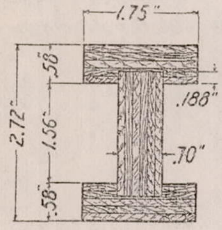
I = 4.91

Section of Beam-III



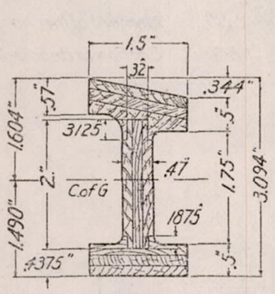
I = 4.466

Section of Beam-IV



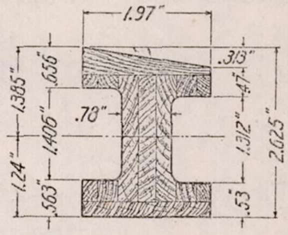
I = 2.6

Section of Beams-V, VI, VII, VIII.



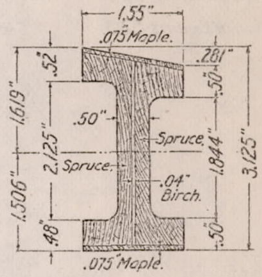
I = 2.594

Section of Beams-IX, X.



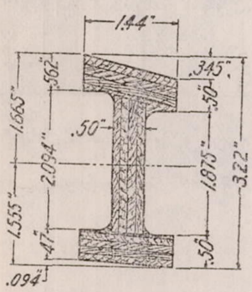
I = 2.312 in.⁴

Section of Beam-XI.



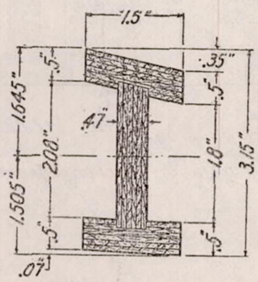
I = 2.64 in.⁴

Section of Beam-XII.



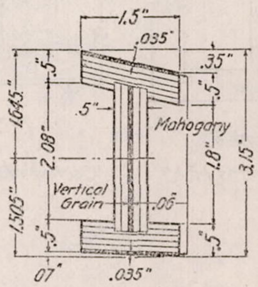
I = 2.633 in.⁴

Section of Beams-XIII, XIV.



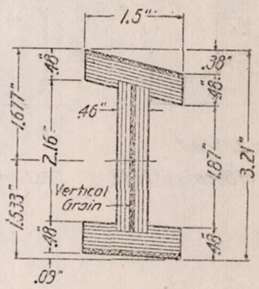
I = 2.67 in.⁴

Section of Beams-XV, XVI



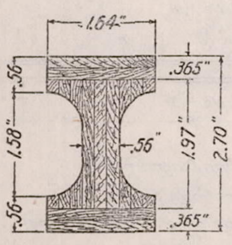
I = 2.67 in.⁴

Section of Beams-XVII, XVIII.



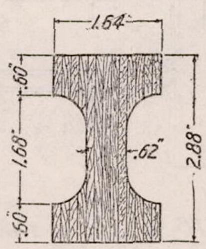
I = 2.68 in.⁴

Section of Beams-XIX, XX.



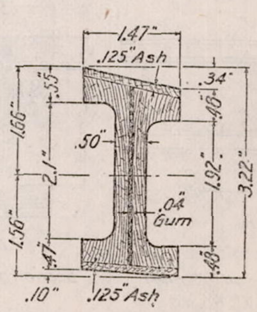
I = 2.400 in.⁴

Section of Beam-XXI.



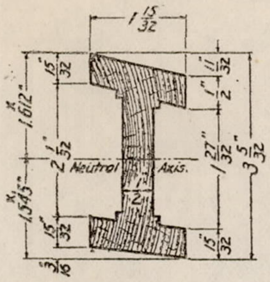
I = 2.937 in.⁴

Section of Beam-XXII.

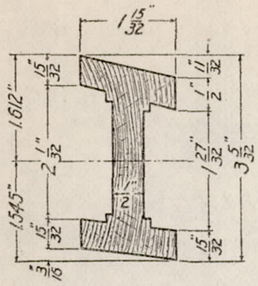


I = 2.63 in.⁴

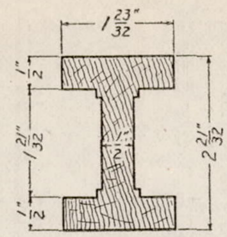
Section of Beam-XXIII



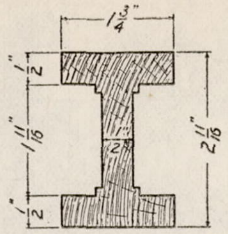
Moment of Inertia = 2.407
Section of Beams 1-2-3.



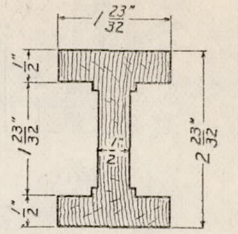
Moment of Inertia = 2.407
Section of Beams 4-5-6.



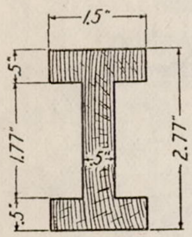
Moment of Inertia = 2.210
Section of Beams 7-8-9.



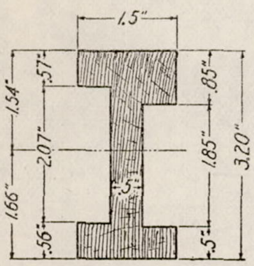
Moment of Inertia = 2.330
Section of Beams 10-11-12.



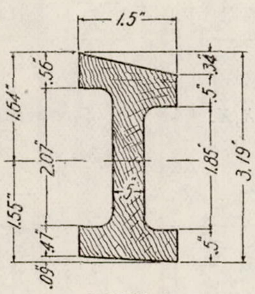
Moment of Inertia = 2.353
Section of Beams 14-15.



I = 2.196 in.[4]
Section of Beams, 1-5, 1-6, 1-7.



I = 3.418 in.[4]
Section of Beams, 1-8, 1-9.



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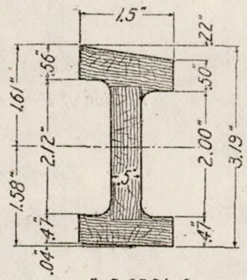
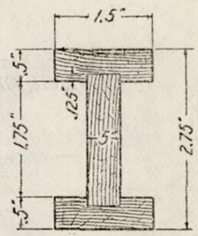
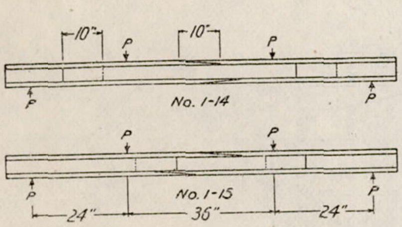
Section of Beams 1-10, 1-11.



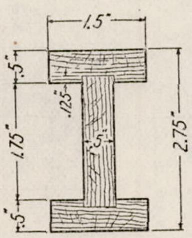
I = 2.820 in.[4]
Section of Beams 1-16, 1-17.



I = 2.154 in.[4]
Section of Beams 1-12, 1-13.



Loading Diagram
and Location of Splices.
(Splices in Web and Flanges are all 10" Long)



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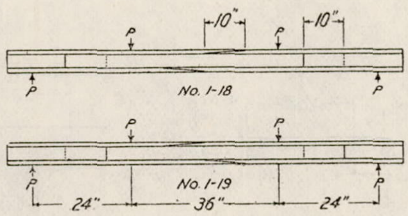
Section of 1-14, 1-15.



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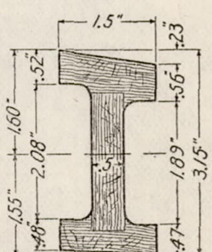
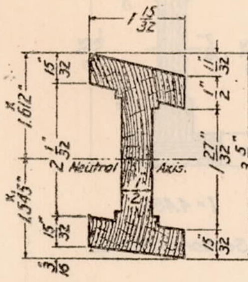
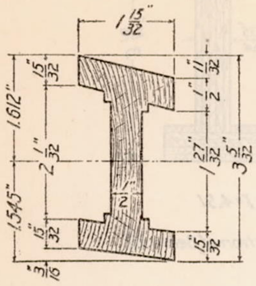


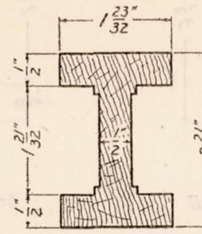
I = 2.724 in[4]
Section of 1-18, 1-19.



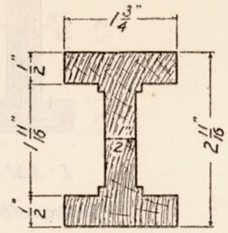
Moment of Inertia = 2.407
Section of Beams - 1-2-3.



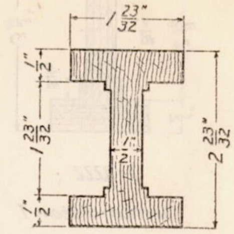
Moment of Inertia = 2.407
Section of Beams - 4-5-6.



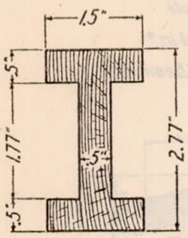
Moment of Inertia = 2.210
Section of Beams - 7-8-9.



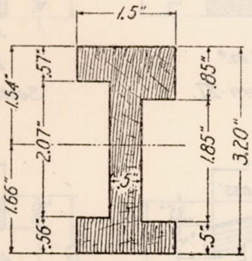
Moment of Inertia = 2.330
Section of Beams - 10-11-12.



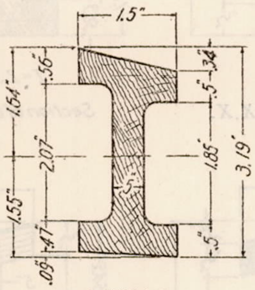
Moment of Inertia = 2.353
Section of Beams - 14-15.



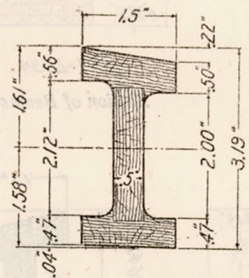
$I = 2.196 \text{ in.}^4$
Section of Beams, I-5, I-6, I-7.



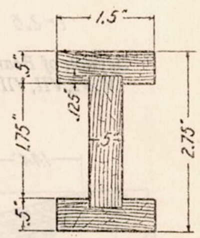
$I = 3.418 \text{ in.}^4$
Section of Beams, I-8, I-9.



$I = 2.78 \text{ in.}^4$
Section of Beams I-10, I-11.



$I = 2.820 \text{ in.}^4$
Section of Beams I-16, I-17.



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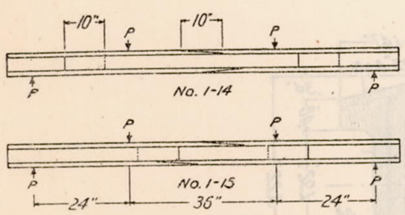
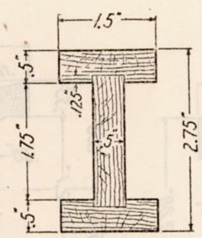
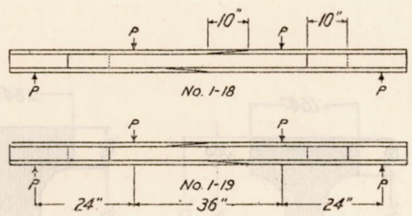
Section of Beams I-12, I-13.



Loading Diagram
and Location of Splices.
(Splices in Web and Flanges are all 10" Long)



$I = 2.154 \text{ in.}^4$
Section of I-14, I-15.



Loading Diagram
and Location of Splices.
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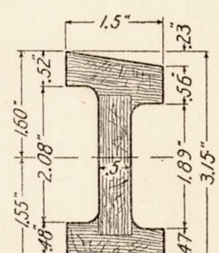
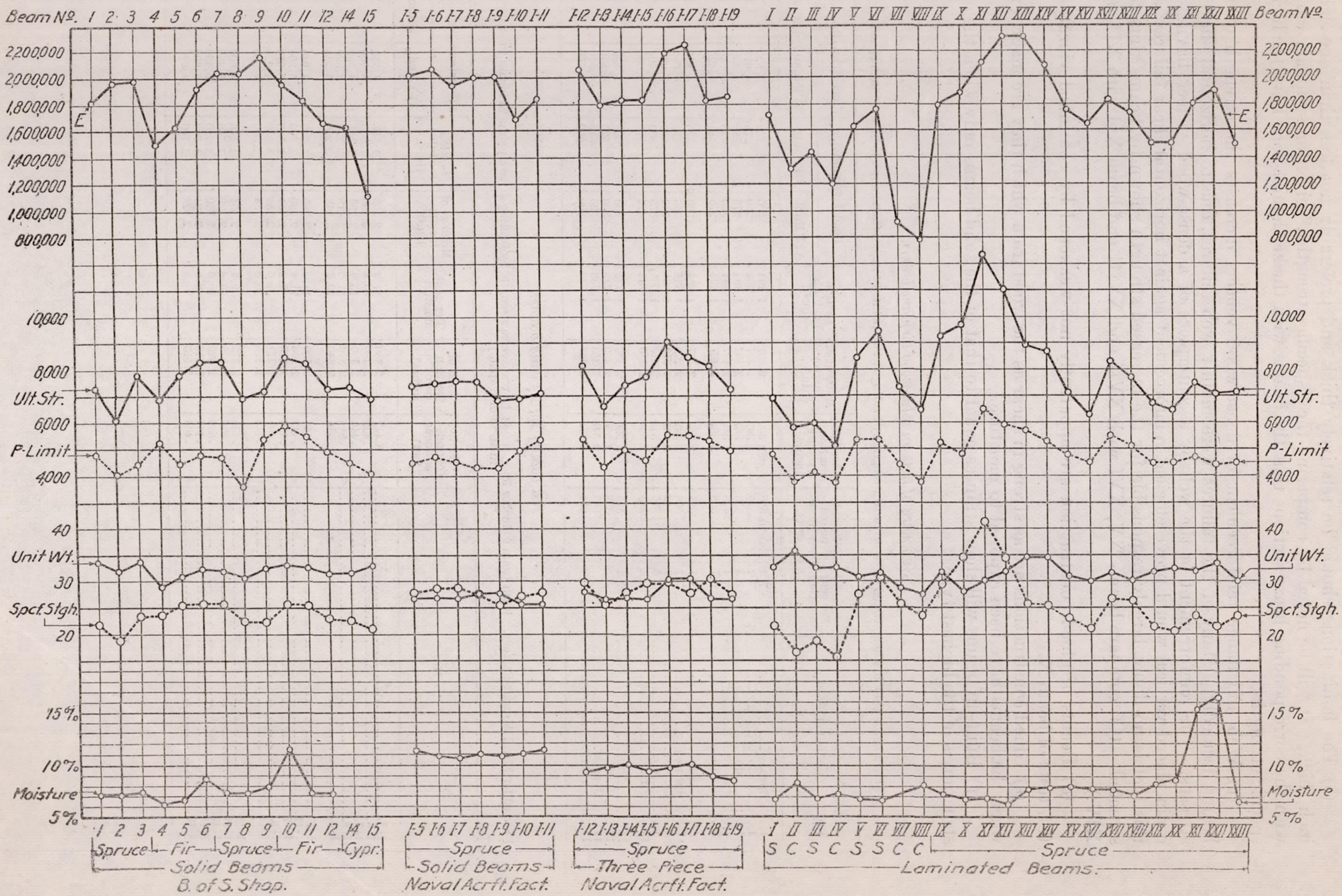


$I = 2.724 \text{ in.}^4$
Section of I-18, I-19.

CHART SHOWING RESULTS OF TESTS ON WOOD AIRPLANE WING BEAMS

E = Modulus of Elasticity, Lbs./Sq. in.
Ult. Str. = Ultimate Breaking Stress, Lbs./Sq. in.
P-Limit = Stress at Elastic Limit, Lbs./Sq. in.

Unit Wt. = Weight of Beam, Lbs./Cu. ft.
Spcf. Stgh. = Specific Strength ÷ 10 = Ult. Str. ÷ Unit Wt. ÷ 10
Moisture = Moisture Content % Dry Weight.



(*b*) The laminations should be relatively thick and preferably not less than one-eighth inch thick. It will be noted by comparing the "specific strengths," given on summary curve, with the corresponding beam sections that the beams with thicker laminations have the higher specific strengths.

(*c*) Web and flange reinforcement of dense-wood veneers increases the strength of the beams decidedly. Many of the failures were mainly web failures, due to horizontal shearing stresses. The reinforcement of the web by a centerpiece of a dense-wood veneer having its grain placed vertical would prove efficient reinforcement against horizontal shear failures; and this fact is no doubt largely responsible for the increased strength shown by beams thus constructed. (Cf. compare beams XV, XVI with XVII and XVIII and beam XII with XIII and XIV.)

(*d*) Beams of glued construction are apparently not weakened by continued vibrations. (Cf. tests of beam X.)

(*e*) Glued constructions are as strong in shear as the wood from which they are made, even when the beams have been exposed to moisture.

(*f*) Built-up beams will show stiffness equal to that of the solid beams only when the construction is of the highest type.

Summary of tests on solid-wood airplane beams.

[Each beam 90 inches long, tested for transverse strength by loading at two points 24 inches from supports in an 84-inch span.]

No.	Kind of wood.	Per cent moisture.	Weight (pounds per linear foot).	Area of section (square inches).	Moment of inertia (in.⁴).	Section modulus (in.³).	Load P (pounds).		Fiber stress (lbs. sq. in.).	
							At P limit.	Ultimate.	At P limit.	Ultimate.
1	Spruce	7.3	0.550	2.362	2.407	1.494	300	450	4,820	7,230
2	do	7.2	.525	2.362	2.407	1.494	250	375	4,010	6,020
3	do	7.5	.550	2.362	2.407	1.494	275	485	4,420	7,800
4	Fir	6.3	.475	2.362	2.407	1.494	325	430	5,220	6,900
5	do	6.7	.508	2.362	2.407	1.494	275	485	4,420	7,800
6	do	8.7	.533	2.362	2.407	1.494	300	520	4,820	8,350
7	Spruce	7.2	.566	2.542	2.210	1.665	325	575	4,690	8,300
8	do	7.2	.542	2.542	2.210	1.665	250	475	3,600	6,850
9	do	7.6	.575	2.542	2.210	1.665	375	500	5,400	7,200
10	Fir	11.6	.583	2.596	2.330	1.735	425	610	5,880	8,450
11	do	7.2	.575	2.596	2.330	1.735	400	600	5,530	8,300
12	do	7.1	.558	2.596	2.330	1.735	350	525	4,840	7,260
14	Cypress		.563	2.574	2.353	1.730	325	525	4,510	7,290
15	do		.584	2.574	2.353	1.730	300	500	4,160	6,940

Test data of spruce wing beams.

[Tested for Naval Aircraft Factory. Each beam 90 inches long, tested for transverse strength by loading at two points 24 inches from supports in an 84-inch span.]

No.	Weight (pounds per linear foot).	Area of section (square inches).	Per cent moisture.	Moment of inertia (in.⁴).	Section modulus (in.³).	Fiber stress (lbs. sq. in.).	
						At P limit.	Ultimate.
I-5	0.442	2.380	11.2	2.196	1.585	4,550	7,400
I-6	.439	2.380	10.8	2.196	1.585	4,700	7,550
I-7	.440	2.380	10.5	2.196	1.585	4,550	7,600
I-8	.543	2.840	11.0	3.418	2.220	4,320	7,540
I-9	.538	2.840	10.7	3.148	2.220	4,320	6,860
I-10	.448	2.500	11.0	2.780	1.700	4,940	6,970
I-11	.442	2.500	11.4	2.780	1.700	5,300	7,050
I-12	.456	2.375	9.2	2.154	1.566	5,370	8,140
I-13	.430	2.375	9.6	2.154	1.566	4,220	6,600
I-14	.445	2.375	10.0	2.154	1.566	4,980	7,400
I-15	.434	2.375	9.3	2.154	1.566	4,600	7,710
I-16	.530	2.525	9.8	2.820	1.750	5,490	9,060
I-17	.530	2.525	10.0	2.820	1.750	5,490	8,440
I-18	.464	2.513	8.9	2.724	1.700	5,300	8,050
I-19	.464	2.513	8.5	2.724	1.700	4,940	7,200

Summary of tests on laminated airplane beams.

[Each beam 90 inches long, tested for transverse strength by loading at two points 24 inches from supports in an 84-inch span.]

No.	Kind of wood.	Per cent moisture.	Weight (pounds per linear foot).	Area of section (square inches).	Moment of inertia (in.^{4}).	Section modulus (in.^{3}.)	Load P (pounds).		Fiber stress (lbs. sq. in.).	
							At P limit.	Ultimate.	At P limit.	Ultimate.
I	Spruce	6.79	0.610	2.674	3.222	2.022	400	585	4,740	6,940
II	Cypress	8.25	.665	2.695	3.370	2.073	325	500	3,770	5,800
III	Spruce	6.54	.690	3,093	4.910	2.661	450	650	4,060	5,860
IV	Cypress	7.35	.656	2,879	4.466	2.842	375	525	3,620	5,060
V	Spruce	6.66	.654	3,121	2,600	1,912	425	670	5,340	8,420
VI	do	6.59	.674	3.121	2.600	1.912	425	750	5,340	9,420
VII	Cypress		.620	3.121	2.600	1.912	350	585	4,400	7,340
VIII	do	8.05	.596	3.121	2.600	1.912	300	523	3,770	6,560
IX	Spruce	7.22	.540	2.495	2.594	1.616	350	620	5,200	9,200
X	do	6.76	.483	2.480	2.600	1.625	325	654	4,800	9,660
XI	do	6.89	.675	3.245	2.312	1.670	450	859	6,460	12,350
XII	do	6.36	.566	2.544	2.640	1.631	400	746	5,890	11,000
XIII	do	7.89	.590	2.451	2.633	1.580	375	589	5,690	8,950
XIV	do	7.89	.590	2.451	2.633	1.580	350	575	5,310	8,740
XV	do	8.00	.520	2.412	2.670	1.624	325	485	4,810	7,170
XVI	do	7.89	.501	2.412	2.670	1.624	300	425	4,440	6,280
XVII	do	7.78	.529	2.412	2.670	1.624	375	565	5,550	8,350
XVIII	do	7.35	.500	2.412	2.670	1.624	350	527	5,170	7,790
XIX	do	8.26	.525	2.366	2.680	1.600	300	450	4,500	6,750
XX	do	8.64	.529	2.366	2.680	1.600	300	437	4,500	6,560
XXI	do	15.50	.632	2.845	2.400	1.780	350	553	4,720	7,460
XXII	do	16.50	.725	3.135	2.937	2.040	375	598	4,420	7,050
XXIII	do	6.65	.508	2.450	2.630	1.585	300	465	4,540	7,040

REMARKS ON TESTS.

Solid beams of Bureau of Standards shop (Nos. 1 to 15).—All solid wood beams of spruce and fir (Nos. 1 to 12) failed in compression. Beam No. 2 was a poor specimen as it contained a pitch pocket; this accounts for failure at such a low load. The solid beam of cypress wood, No. 14, failed in tension and horizontal shear. Cypress beam No. 15 failed in tension.

Solid beams from Naval Aircraft Factory (Nos. I–6 to I–11).—Each of these beams failed in compression. The compression failures in beams I–5 and I–7 were followed by horizontal shear failures. These beams ran quite uniform, as is shown by the values for "specific strength" on the summary chart of results.

Three-piece beams from Naval Aircraft Factory (Nos. I–12 to I–19).—Each of these beams failed in compression. Failure was not due to splices in the case of the spliced beams (Nos. I–14, I–15, I–18, and I–19). While these beams do not run as uniform in strength as the solid beams above, the variation is not greater than is to be expected in wood. Moreover, the average specific strengths of the three-piece beams is a trifle greater than for the solid beams.

Laminated beams.—Beams I and III of spruce and II and IV of cypress failed in compression. These beams were poorly constructed. A number of laminations in each beam were spliced; the splices were butt joints which were not closely butted. Consequently failure in each beam occurred at a lamination splice.

Beams V and VI were better constructed and were equal to solid wood in specific strength.

Beams VII and VIII of cypress wood failed in tension. The wood in these beams was of poor quality and appeared to be decayed.

Beam No. X failed in compression.—Beam No. X was given a vibratory or repeated stress test before being subjected to the regular transverse test. The purpose was to determine whether or not the stiffness or strength of the beam would be affected by a test of this nature. The results indicate that the vibratory test had no effect upon the beam. The vibratory test was not of a very severe nature. This beam failed in compression at the center, and in shear over the entire length of the web. The beam contained no splices in the laminations.

Beam No. XI was a rear wing beam of a larger section than the other beams. This beam carried an exceedingly high load.

Beam No. XII, although classed as a laminated beam, is quite different from the others. The birch lamination or veneer in the center has the grain running in the direction of the depth of the beam section. This beam was bowed laterally to the extent of $\frac{9}{32}$ inch at the center

and the left side of the section was cracked in the web from the birch veneer center to the outside for the entire length, as shown in the photograph. The left side was on the convex side of the bow. In spite of these defects, this beam carried a very high load, which shows that this is a very good type of construction.

Beams XIII and XIV both failed in compression. While these beams were not as strong as some of the preceeding ones, they are practically equal in strength to the solid wood beams.

Beams XV and XVI were not as strong as solid wood beams. This was evidently due to the facts that the lamination splices were poorly made and that the laminations are too thin. Failure occurred at lamination splices.

Beams XVII and XVIII are equal to solid wood beams. These two beams contained poor lamination splices, practically the same as beams XV and XVI. The superiority of these beams over beams XV and XVI was due to the mahogany caps on the top and bottom and the mahogany veneer in the center. Failure occurred at lamination splices.

Beams XIX and XX were inferior to solid wood beams even though they had mahogany caps and veneer. This is undoubtedly due to the fact that the laminations were too thin. Beam XIX failed at a lamination splice, but XX did not.

Beams XXI and XXII were built similar to beam XI. Both failed in compression; failures occurred very slowly. These beams were both inferior to solid wood beams. This was probably due to the high moisture content as is shown on the chart of results.

Beam No. XXIII was built similar to beam XXII, and in addition each half of the section was spliced, splices being located at points of maximum moments. This beam proved to be inferior to solid wood beams due to poorly selected wood and not to the fact that it contained splices. The spruce wood was grained diagonally, the grain sloping 1 in 10; the veneer was soft gum wood having a low shear strength; and the caps were of ash, which is not suitable for this purpose. The results of this test demonstrate that this type of beam can be spliced without causing a weak point.

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